Non-Standard Interactions: Current Status & Future Prospects

Sushant Raut

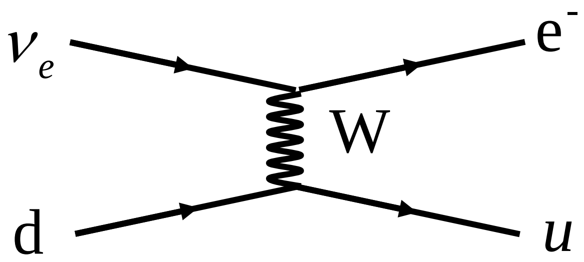
KTH Royal Institute of Technology, Stockholm

Outline

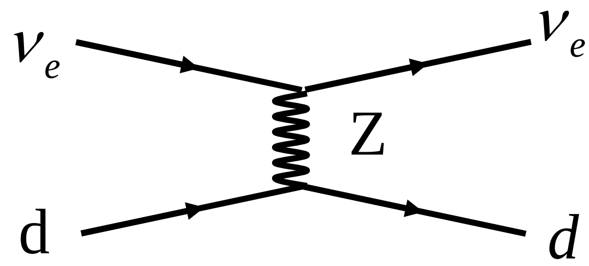
- Non-standard neutrino interactions (NSIs)
- Neutrino oscillations with NSIs
- Current status
- Future prospects
- Probing NSIs at the ESSνSB experiment
- Conclusions (and comments)

Non-standard neutrino interactions: NSIs

- In the Standard Model,



$$\mathcal{L}_{CC} = (\overline{\ell_{\alpha}}\gamma^{\mu} P_L \nu_{\alpha})(\overline{f}\gamma_{\mu} P_L f')$$



$$\mathcal{L}_{NC} = (\overline{\nu_{\alpha}}\gamma^{\mu} P_L \nu_{\alpha})(\overline{f}\gamma_{\mu} P_L f')$$

Non-standard neutrino interactions: NSIs

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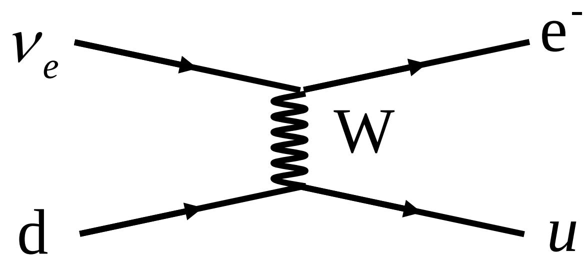

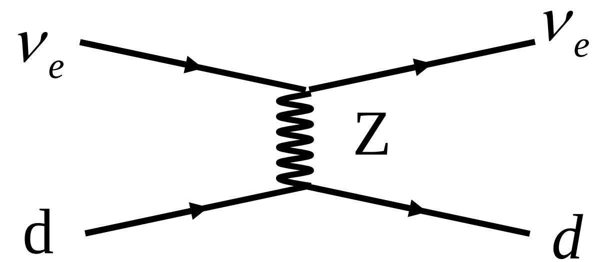

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$$\mathcal{L}_{NC} = (\overline{\nu_{\alpha}}\gamma^{\mu} P_L \nu_{\alpha})(\bar{f}\gamma_{\mu} P_L f')$$

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell_{\alpha}}\gamma^{\mu} P_L \nu_{\beta})(\bar{f}\gamma_{\mu} P_{L,R} f')$$

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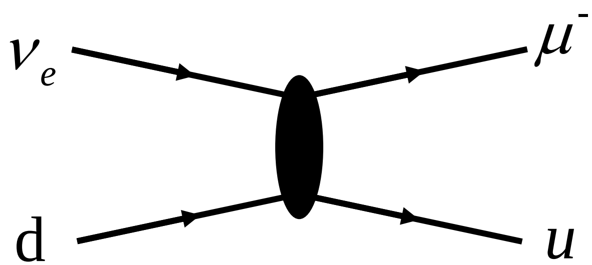

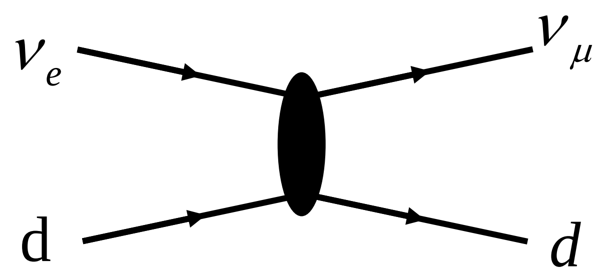

Non-standard neutrino interactions: NSIs

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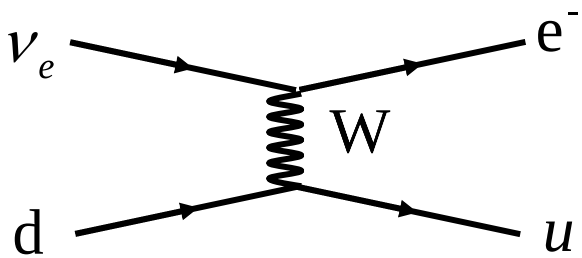

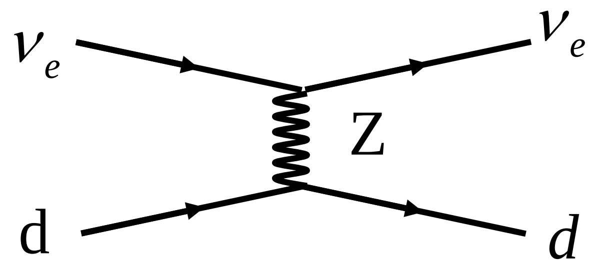

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$

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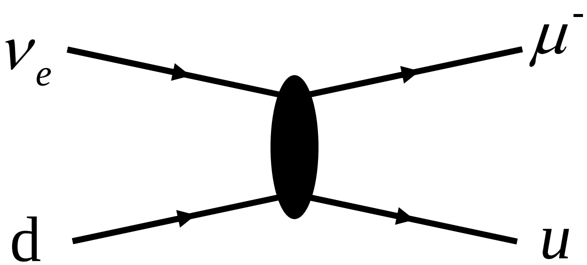

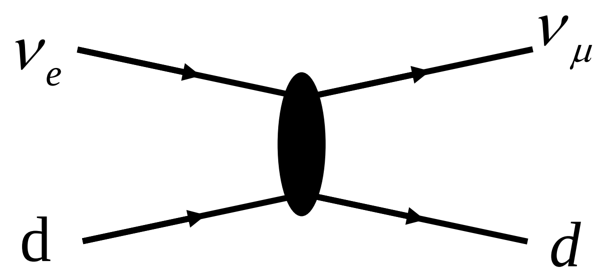

production, detection

propagation

Neutrino oscillations with NSIs

- Neutrino states at the source and detector:

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\alpha\gamma}^s |\nu_\gamma\rangle \quad ; \quad \langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\beta\gamma}^d \langle\nu_\gamma|$$

- Matter effects in the presence of NSIs:

$$A^{NSI} = \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + A \begin{pmatrix} \varepsilon_{ee}^m & \varepsilon_{e\mu}^m & \varepsilon_{e\tau}^m \\ \varepsilon_{\mu e}^m & \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{\tau e}^m & \varepsilon_{\tau\mu}^m & \varepsilon_{\tau\tau}^m \end{pmatrix}$$

- 9x2 (source) + 9x2 (detector) + 9 (propagation) new NSI parameters

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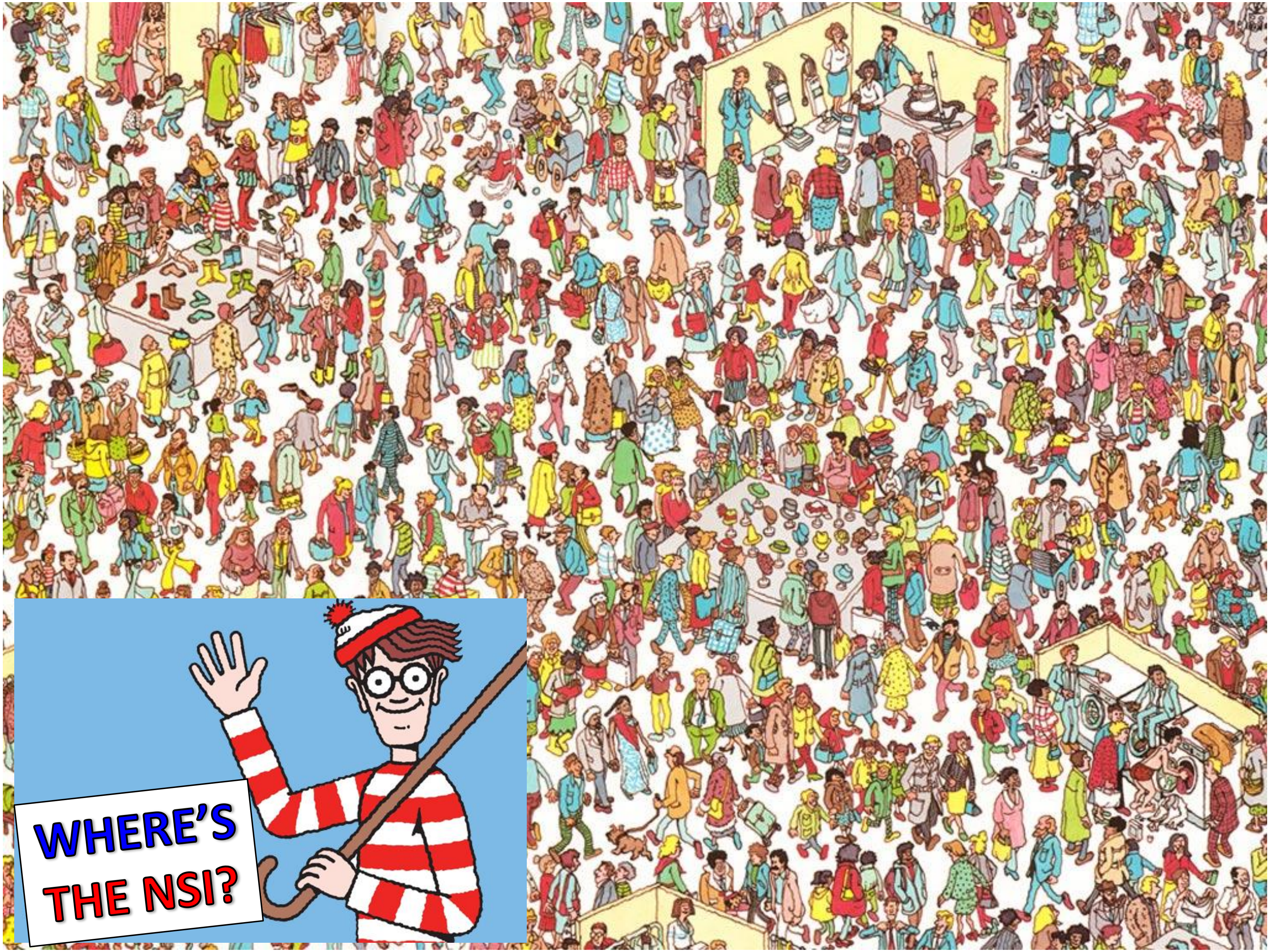
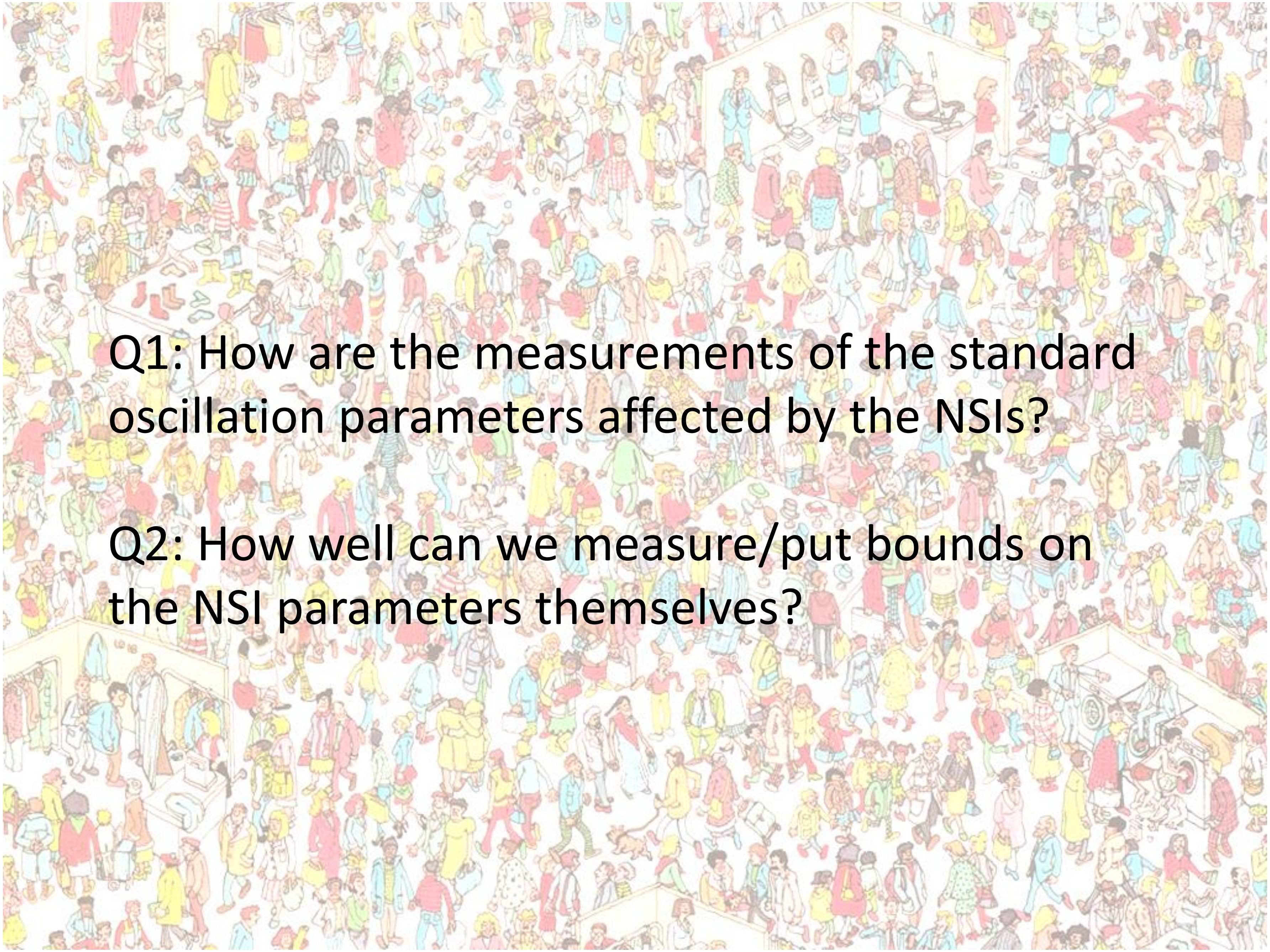
- 9x2 (source) + 9x2 (detector) + 9 (propagation) new NSI parameters

... a slight expansion of the parameter space!


WHERE'S
THE NSI?



Q1: How are the measurements of the standard oscillation parameters affected by the NSIs?

Q2: How well can we measure/put bounds on the NSI parameters themselves?

Current experiments **Future experiments**

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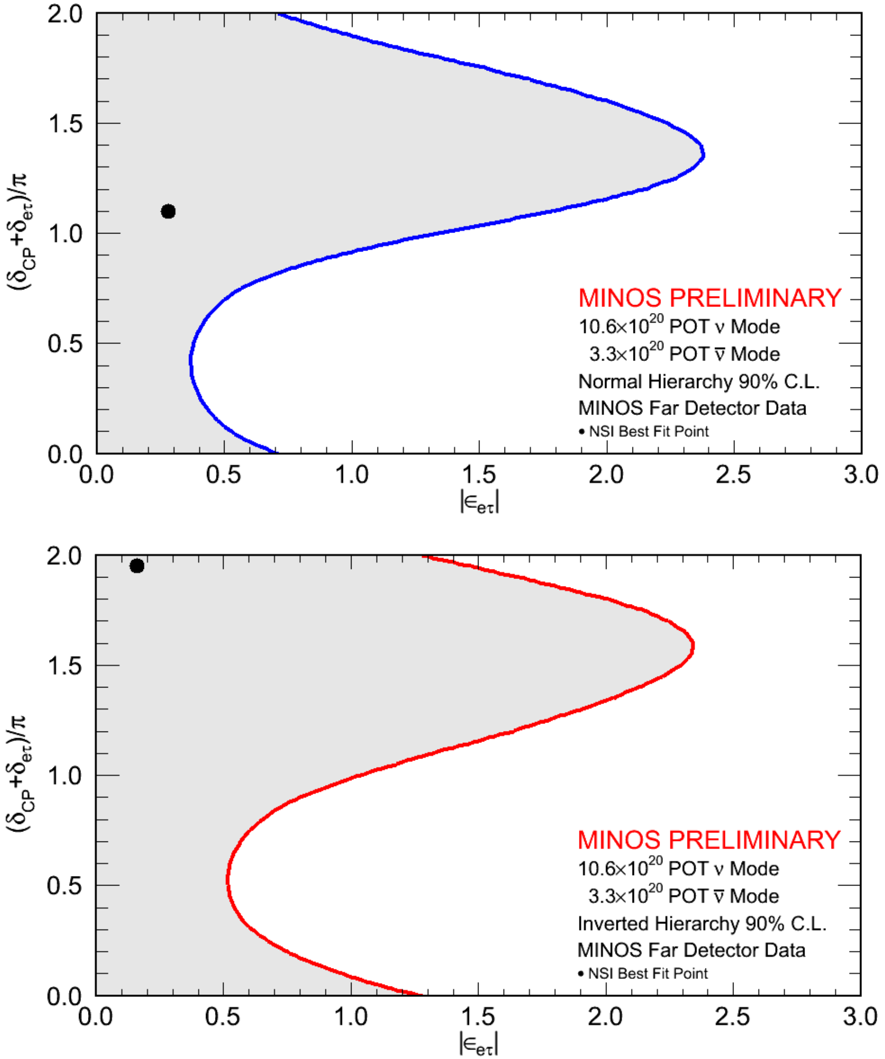
Q2: How well can we measure/put bounds on the NSI parameters themselves?

Remember that the search for NSIs is essentially a search for new physics: complementary to LHC

Current experiments



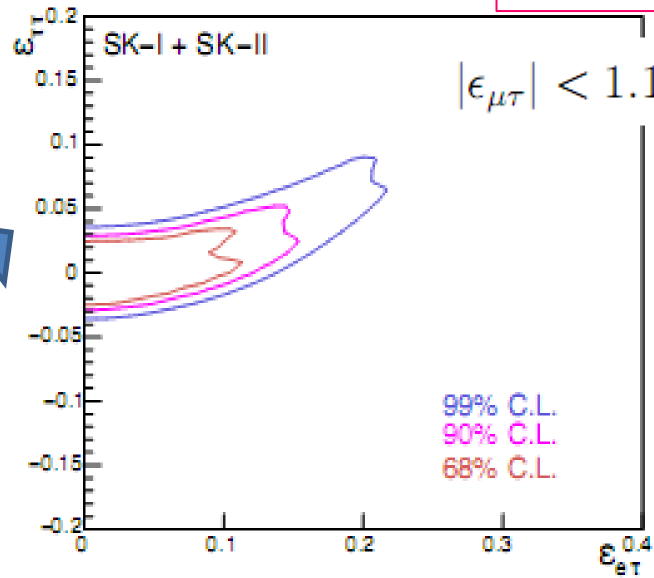
MINOS beam data

Remember: Stringent constraints from the charged lepton sector!

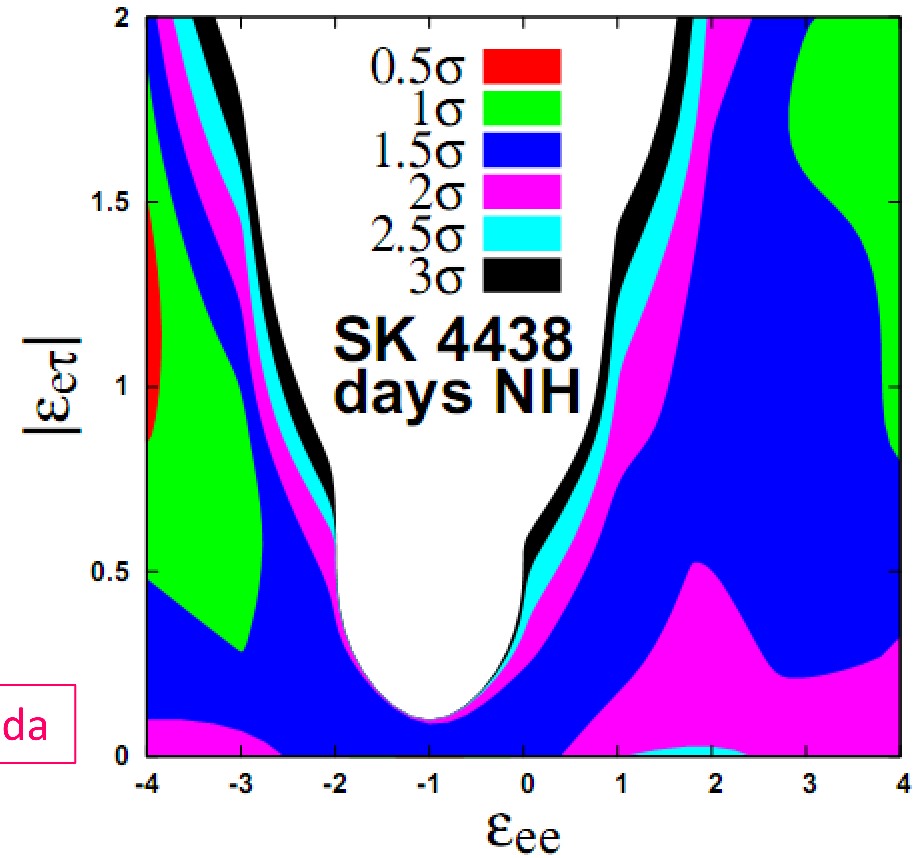
Current experiments

1109.1889: Mitsuka et al.

$$|\epsilon_{\mu\tau}| < 1.1 \times 10^{-2}, \qquad |\epsilon'| = |\epsilon_{\mu\mu} - \epsilon_{\tau\tau}| < 4.9 \times 10^{-2}$$

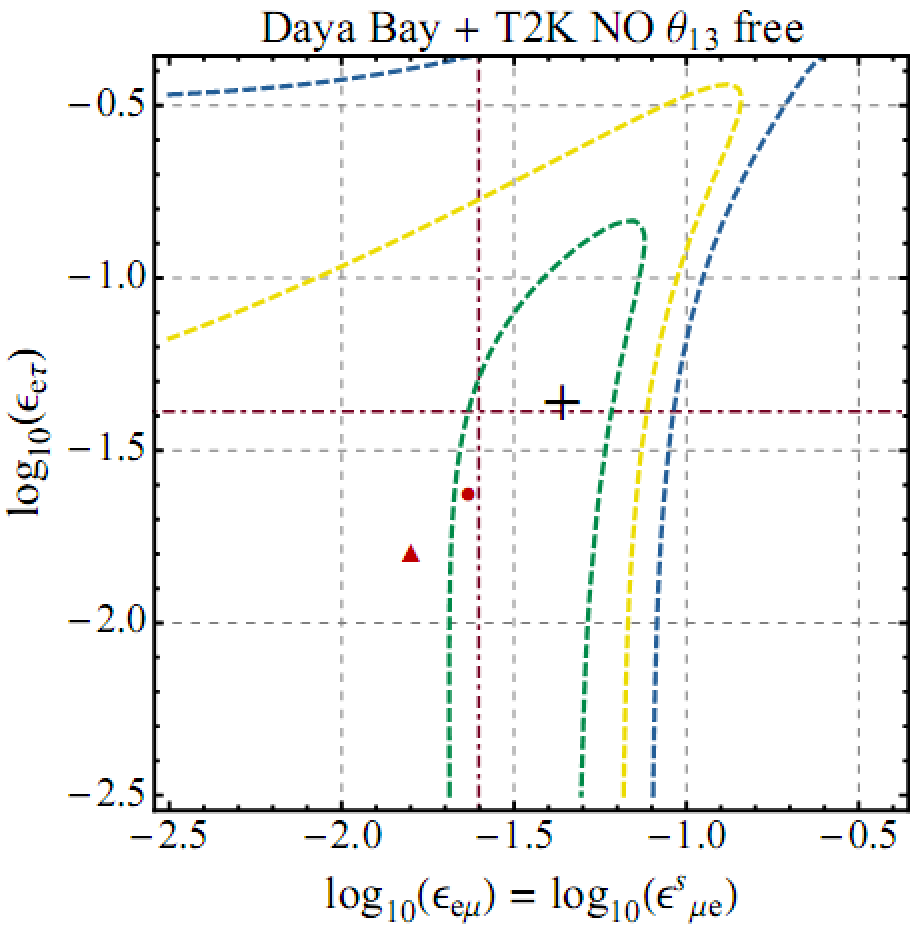


$(\mathrm{d})\varepsilon_{ee} = 0.25$



1503.08056: Fukasawa, Yasuda

Current experiments



Discrepancy between θ_{13} value measured at T2K and at the reactor experiments: role of NSIs

1405.0416: Girardi, Meloni, Petcov

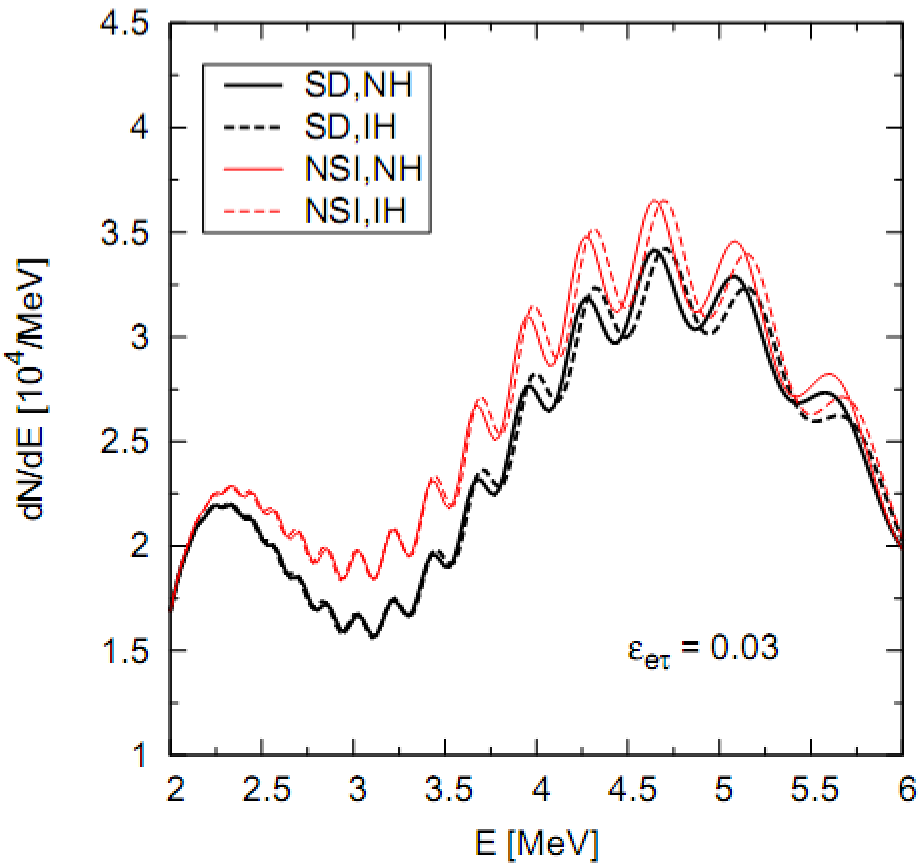
Current experiments

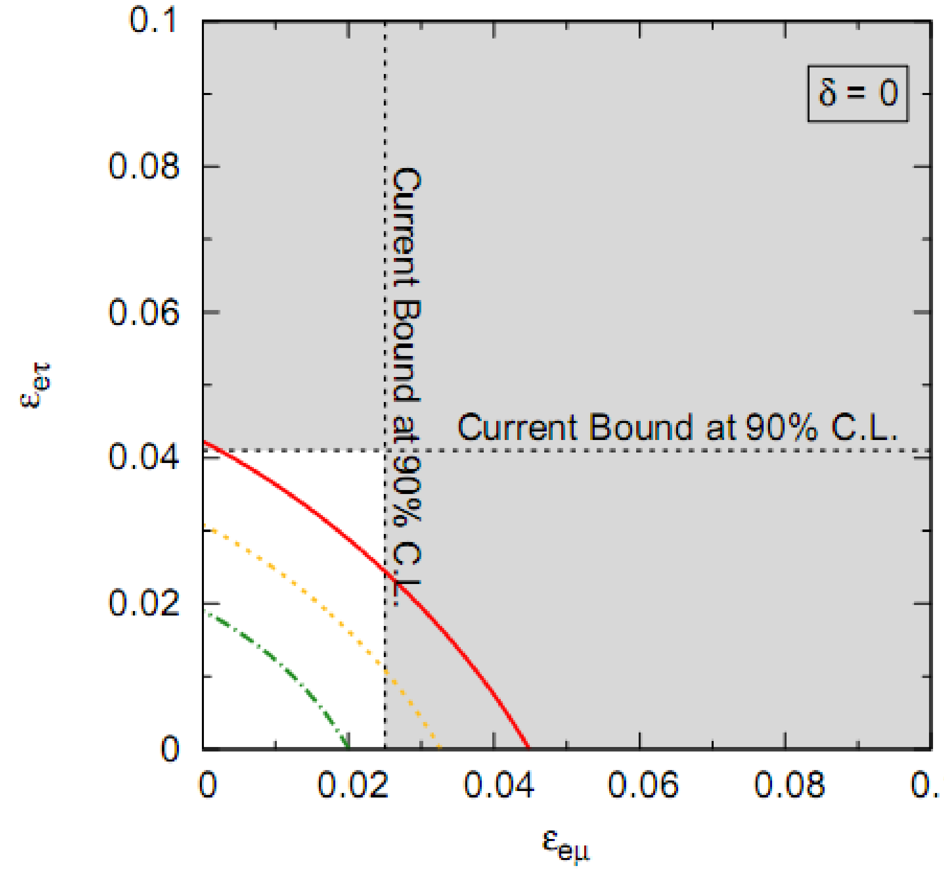
- CKM unitarity
- Pion decays
- Zero distance oscillations at KARMEN, NOMAD
- Loop bounds

$$|\varepsilon^{ud}_{\alpha\beta}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \begin{matrix} 1.8 \cdot 10^{-6} \\ 0.026 \end{matrix} & 0.078 & 0.013 \\ \begin{matrix} 0.087 \\ 0.12 \end{matrix} & \begin{matrix} 0.013 \\ 0.018 \end{matrix} & 0.13 \end{pmatrix}$$

0907.0097: Biggio, Blennow, Fernandez-Martinez

Future prospects



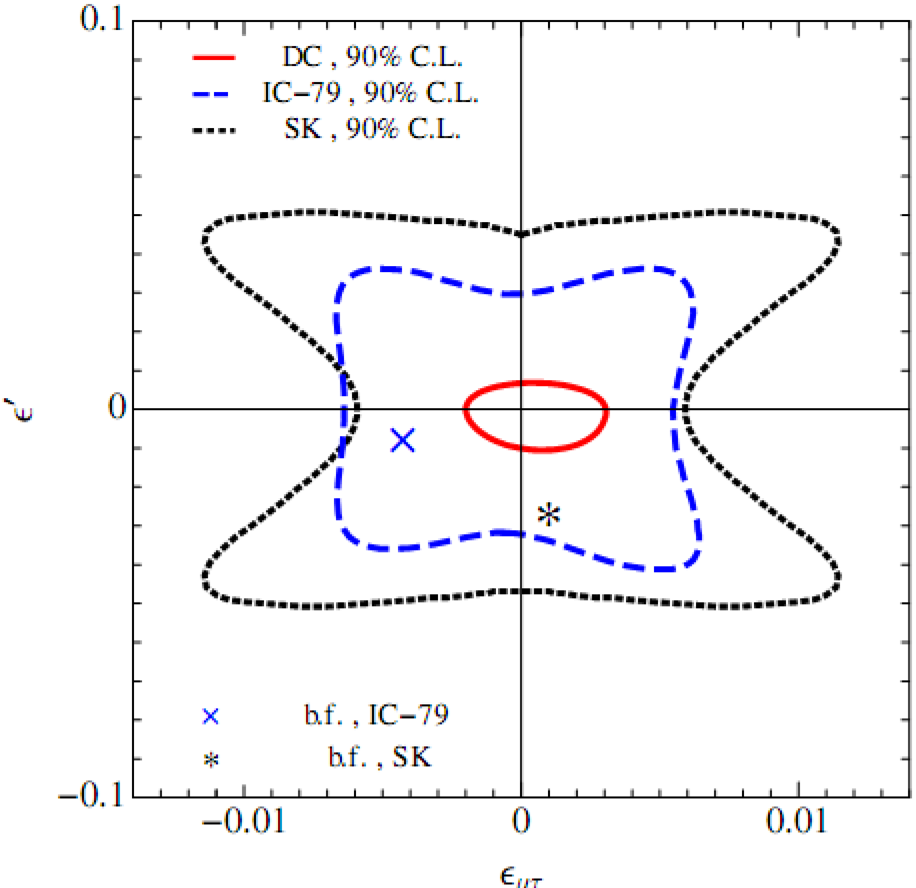


Medium baseline reactors: JUNO

1310.5917: Ohlsson, Zhang, Zhou

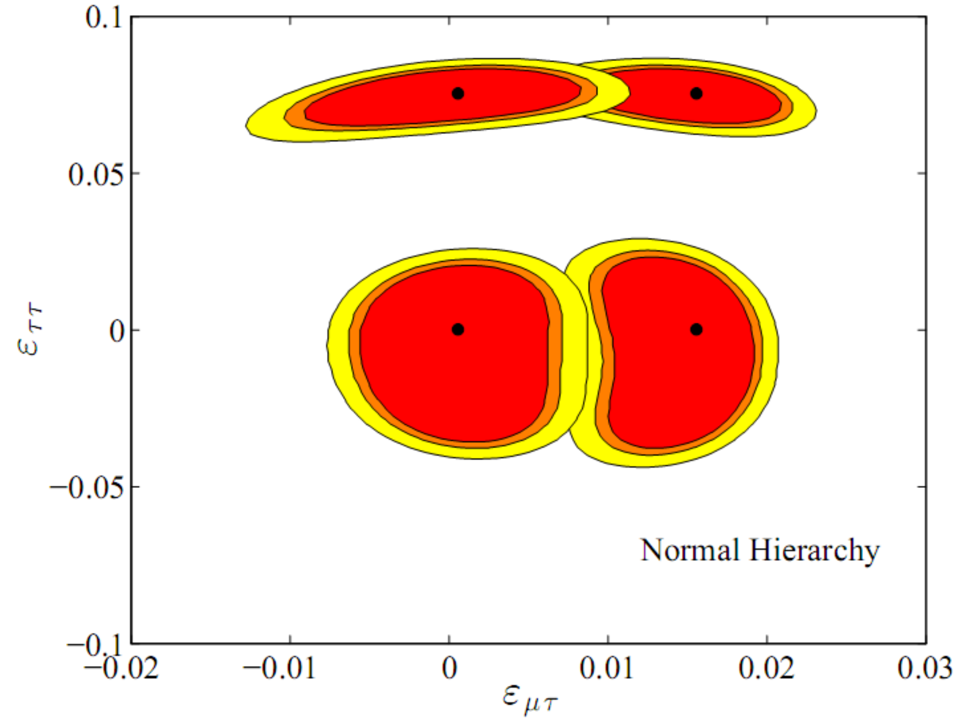
Future prospects

IceCube & Deep Core



1304.1042: Esmaili, Smirnov

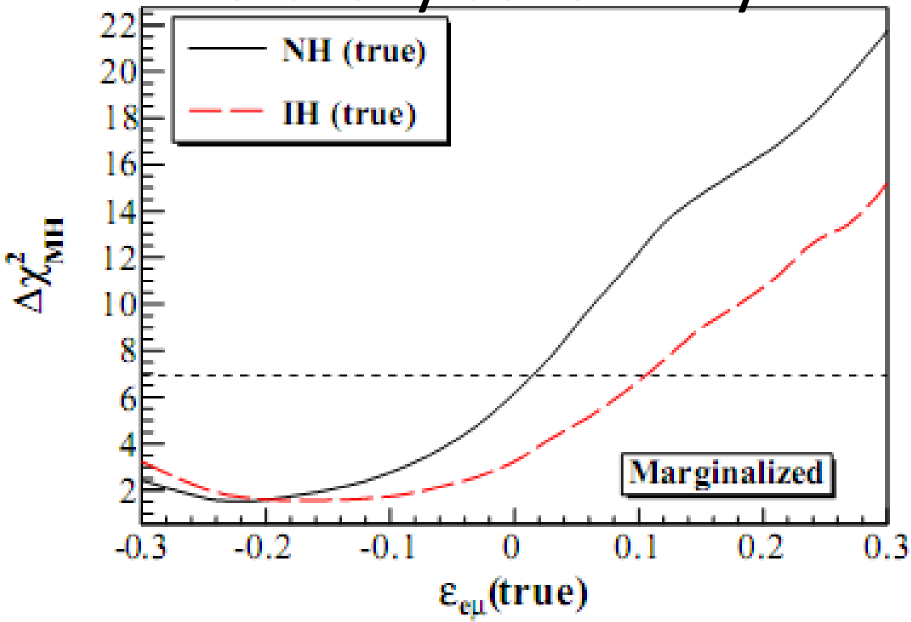
PINGU

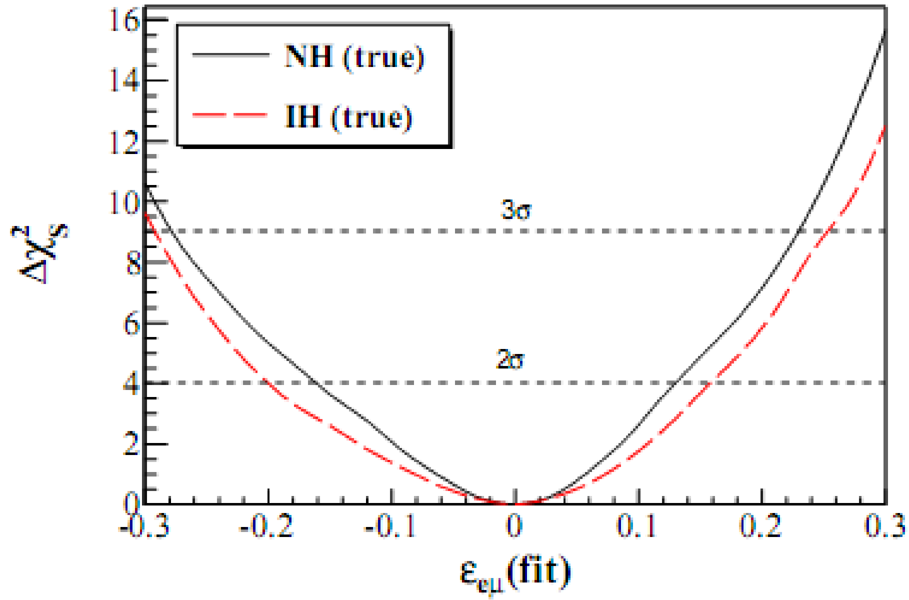


1410.0410: Choubey, Ohlsson

Future prospects

Hierarchy sensitivity

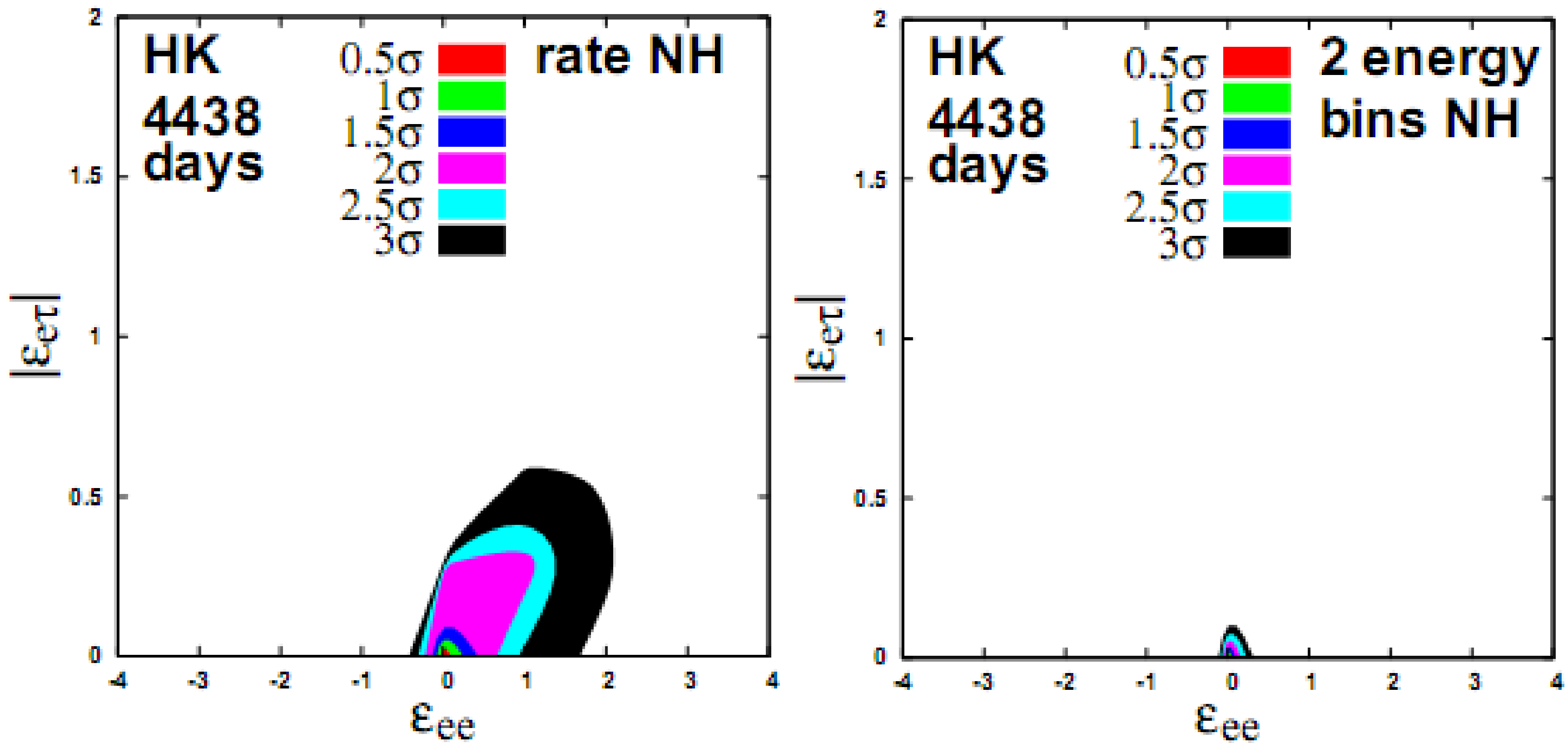




ICAL @ INO

1507.02211: Choubey, Ghosh, Ohlsson, Tiwari

Future prospects



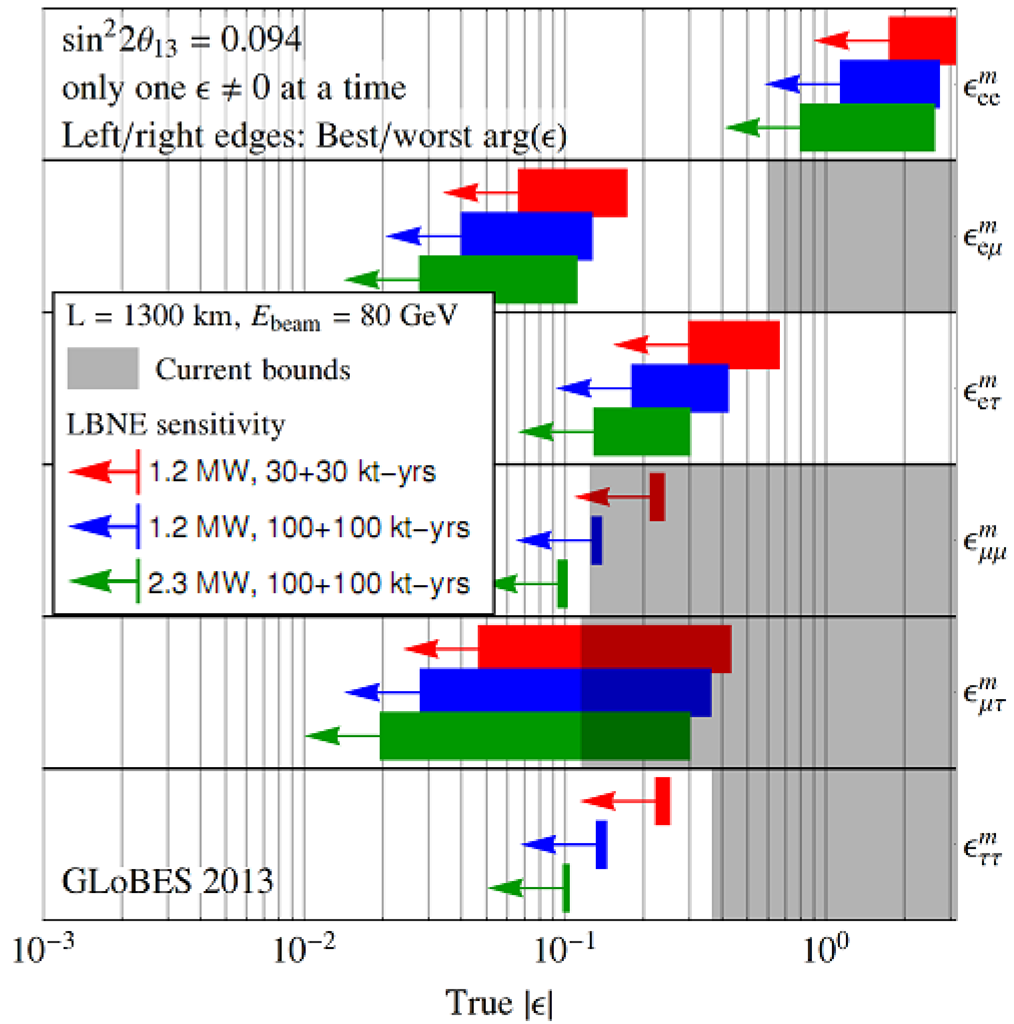
1503.08056: Fukasawa, Yasuda

Future prospects

LBNE/LBNF/DUNE

1307.7335: Adams et al.

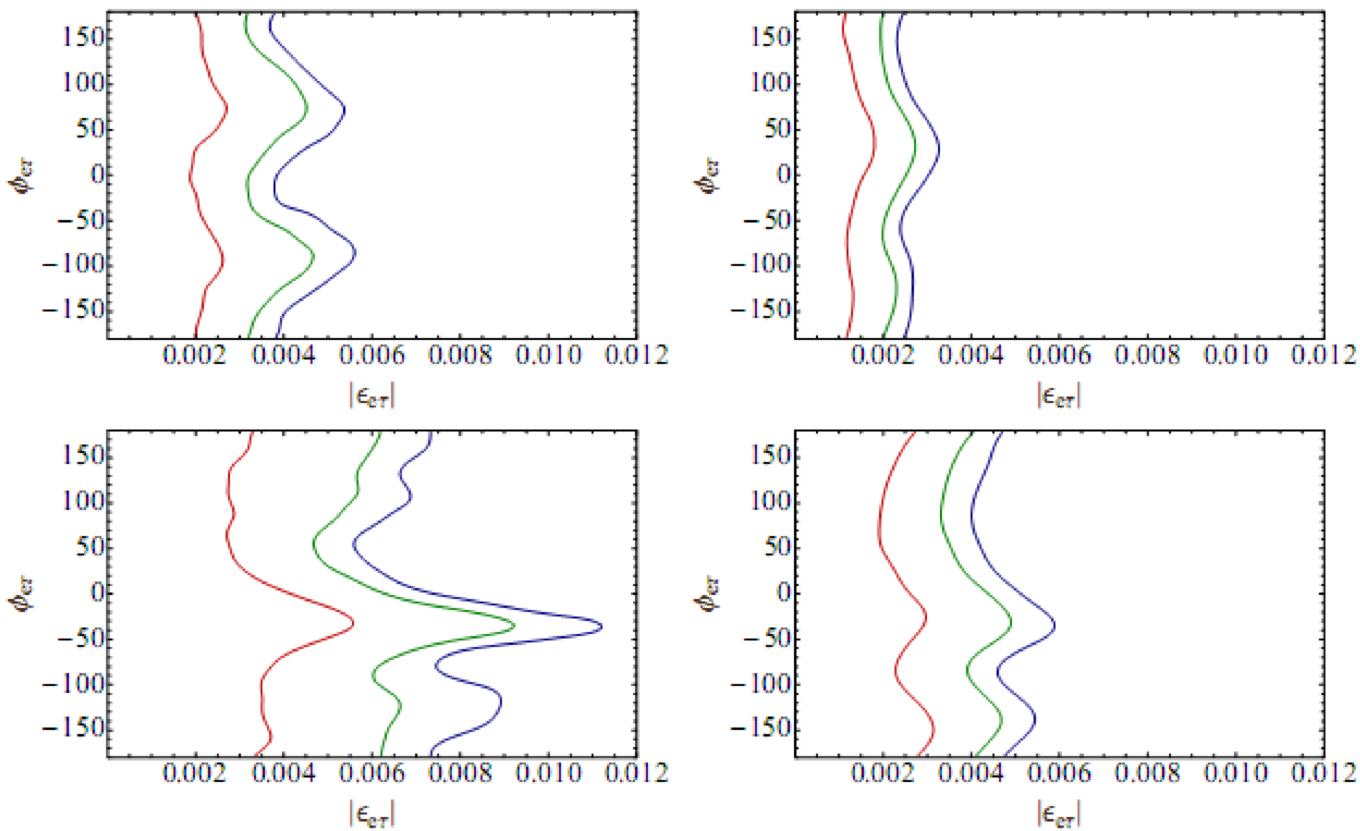
NC NSI discovery reach (3σ C.L.)



Future prospects

Neutrino Factory: 4000 km

1105.5936: Coloma, Donini, Lopez-Pavon, Minakata



$\theta_{13}=0^o$

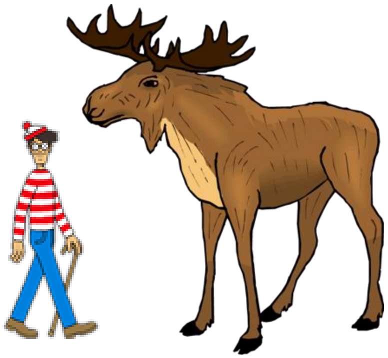
$\theta_{13}=3^o$

IDS25

IDS50

Probing NSIs at ESSνSB

1507.02868: Blennow, Choubey, Ohlsson, SR



The proposed ESSνSB experiment

- European Spallation Source (ESS): under construction in Lund, Sweden
- Proposal to use the proton beam to produce a beam of neutrinos – peak energy 250 MeV
- Possible site for detector: mine in Garpenberg, Sweden – 540 km
- The mine can host a MEMPHYS-like Water Cerenkov detector

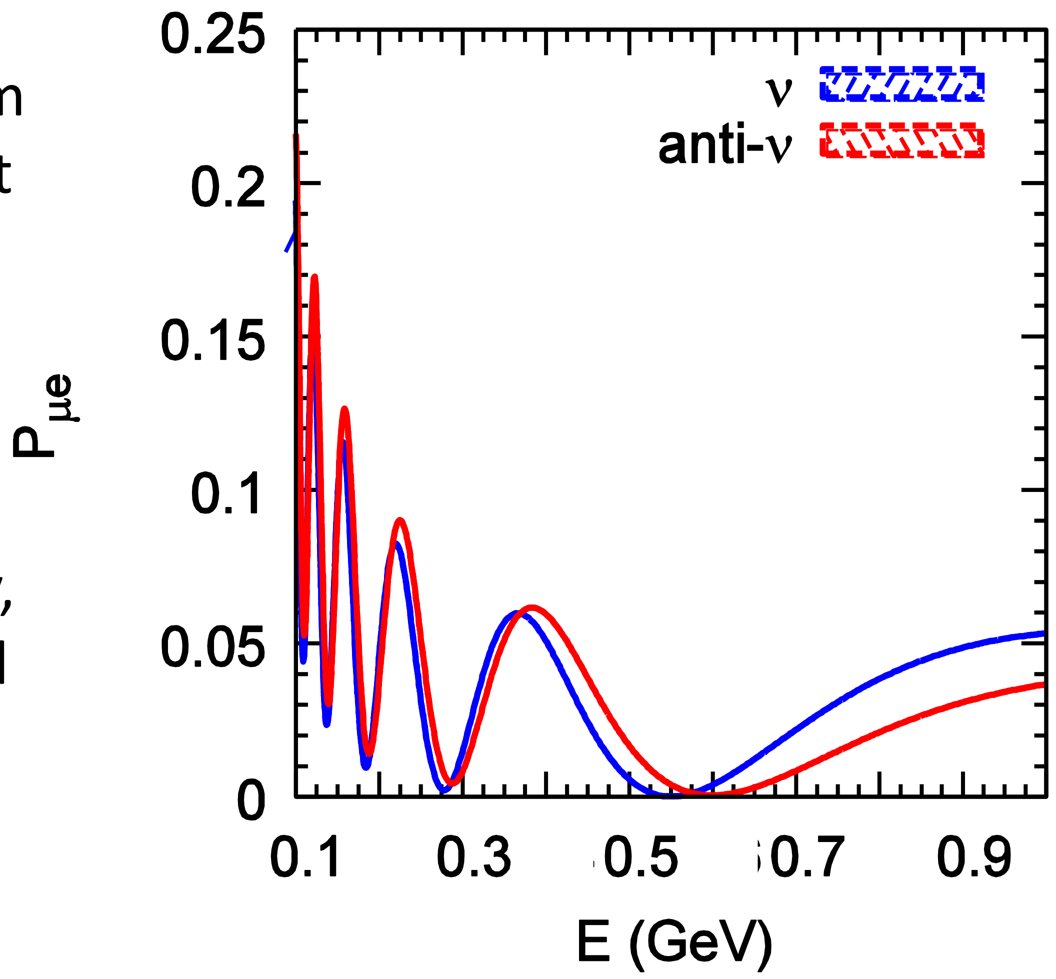
1309.7022: Baussan et al.

ESSνSB

- For a 540 km baseline, the second oscillation maximum (which is sensitive to δ) is at 400 MeV

- The peak energy of the ESSνSB unoscillated spectrum lies at this energy, giving this experiment good sensitivity to δ

- How will this sensitivity be affected by NSIs? Can we use ESSνSB to measure NSIs?



Neutrino oscillations with NSIs

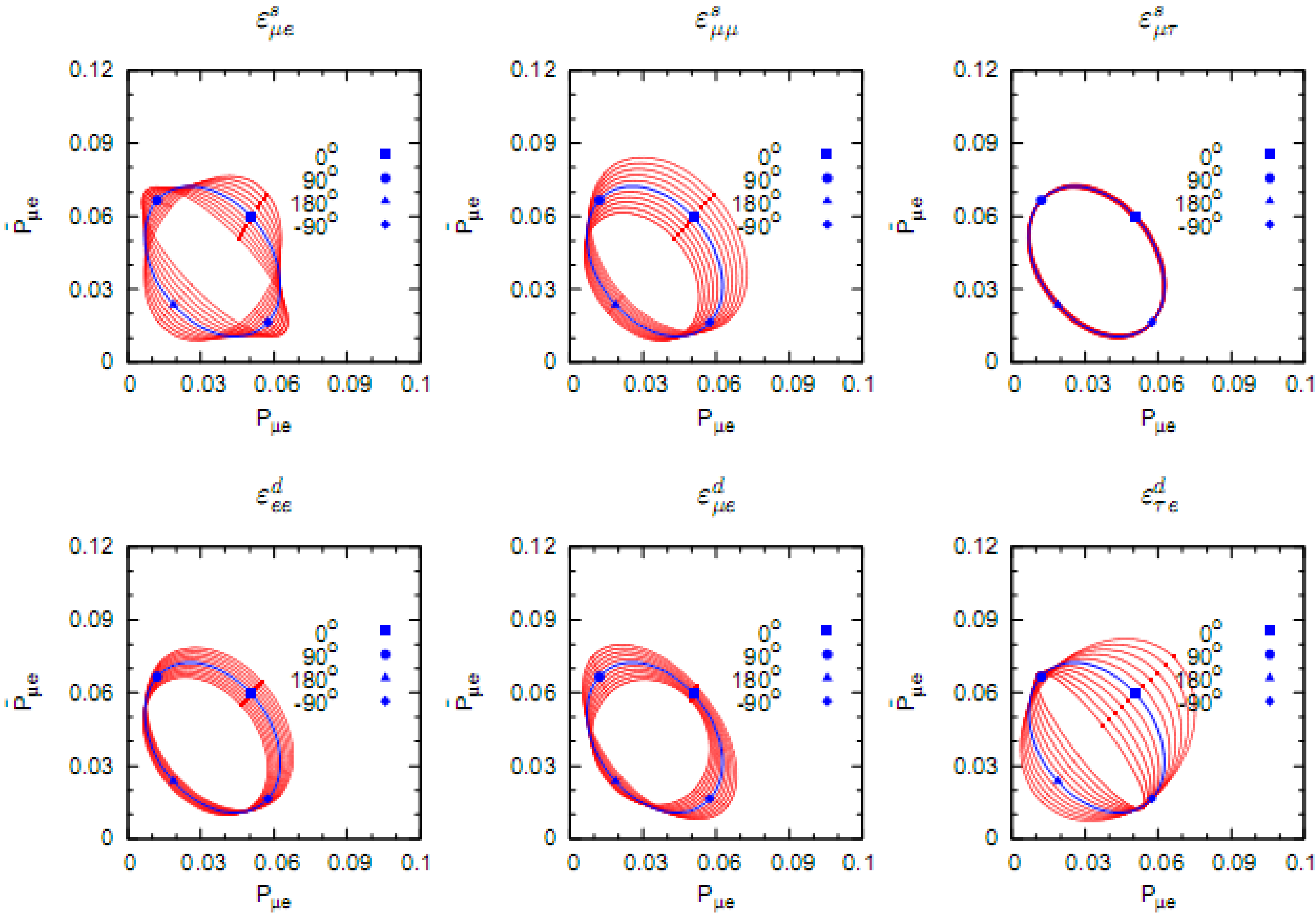
- Propagation NSIs are only relevant for large matter effects and high energy. Therefore we only consider source and detector NSIs here.

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\alpha\gamma}^s |\nu_\gamma\rangle \quad ; \quad \langle\nu_\beta^d| = \langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \varepsilon_{\beta\gamma}^d \langle\nu_\gamma|$$

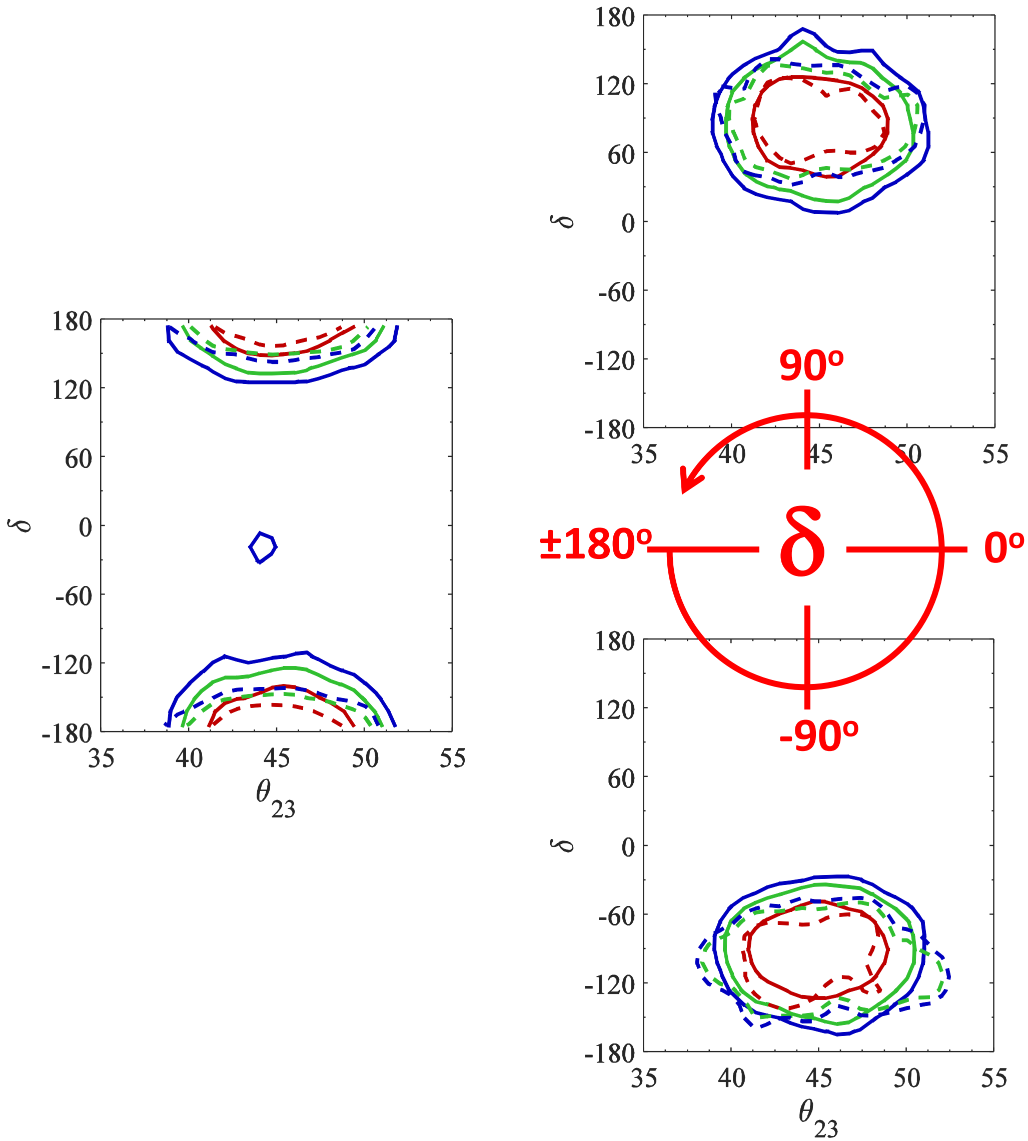
- Since ESSνSB will only observe $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ channels, the relevant NSI parameters are

$$\begin{pmatrix} \varepsilon_{ee}^s & \varepsilon_{e\mu}^s & \varepsilon_{e\tau}^s \\ \varepsilon_{\mu e}^s & \varepsilon_{\mu\mu}^s & \varepsilon_{\mu\tau}^s \\ \varepsilon_{\tau e}^s & \varepsilon_{\tau\mu}^s & \varepsilon_{\tau\tau}^s \end{pmatrix} \quad ; \quad \begin{pmatrix} \varepsilon_{ee}^d & \varepsilon_{e\mu}^d & \varepsilon_{e\tau}^d \\ \varepsilon_{\mu e}^d & \varepsilon_{\mu\mu}^d & \varepsilon_{\mu\tau}^d \\ \varepsilon_{\tau e}^d & \varepsilon_{\tau\mu}^d & \varepsilon_{\tau\tau}^d \end{pmatrix}$$

Interplay of NSI parameters with δ



Results

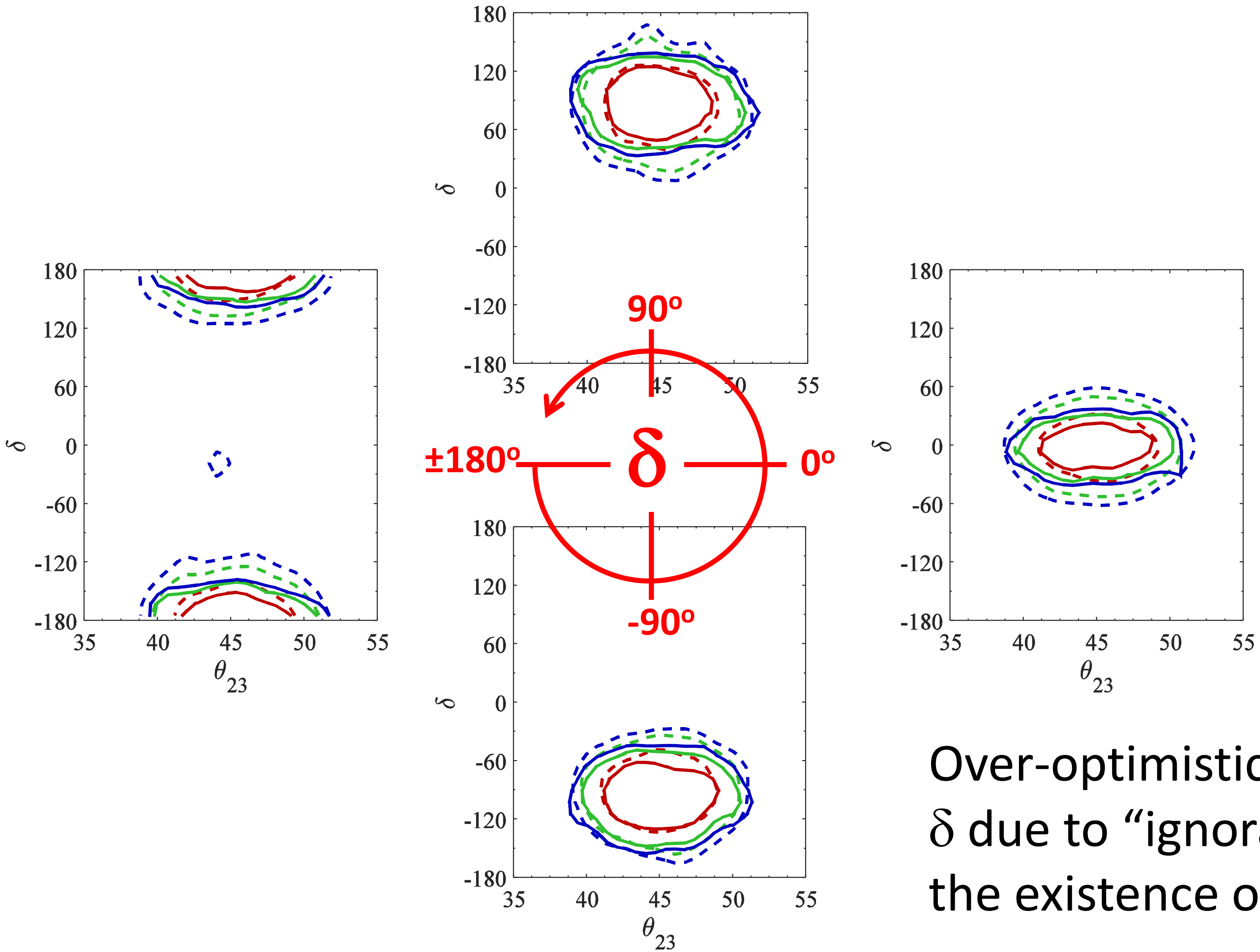


Worsening of δ-precision because of NSIs

Results

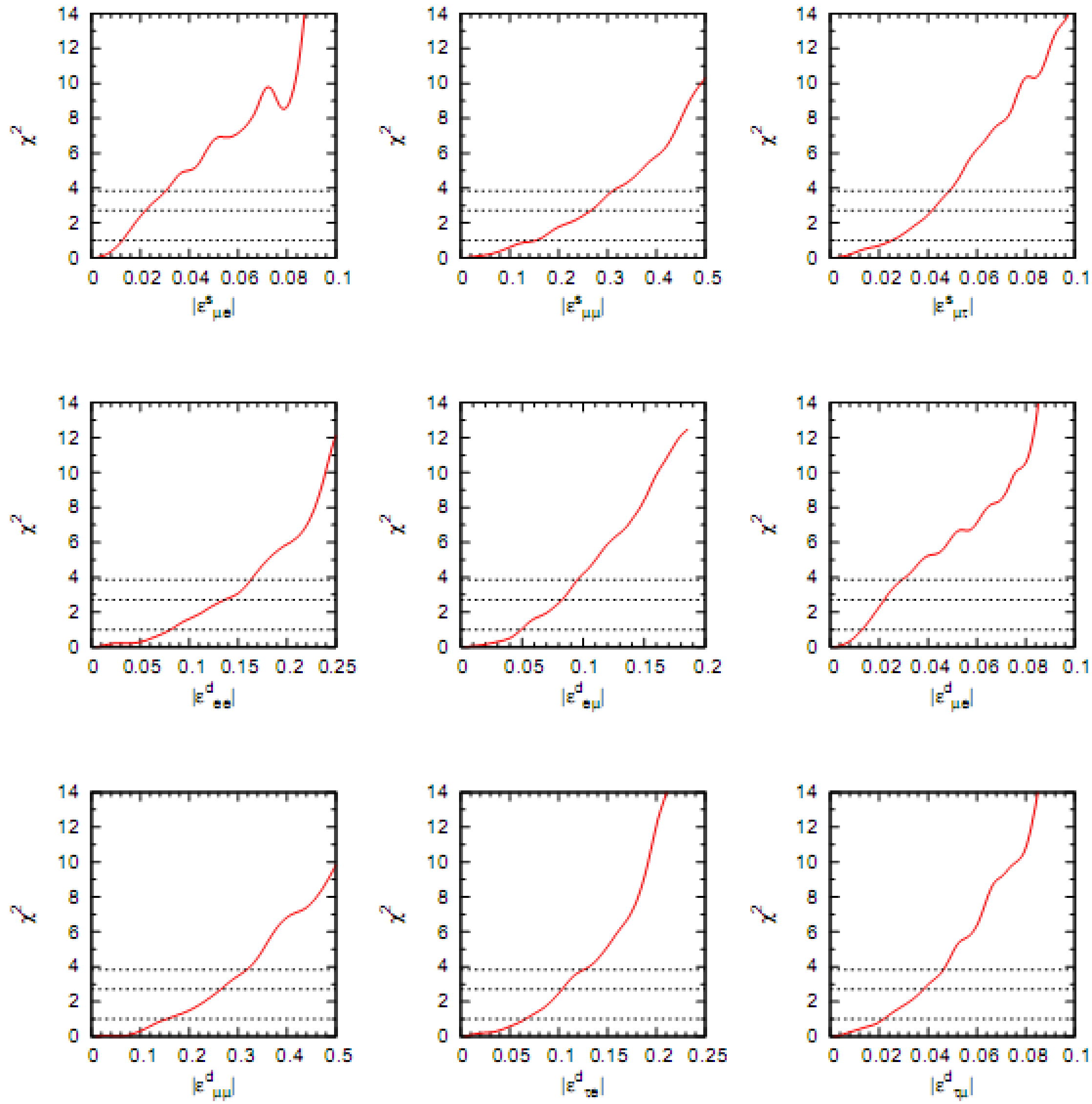
- Salient features:
  - Same features seen across all θ_{23}
  - θ_{23}-precision is largely unaffected by NSIs
  - Worsening of δ -precision is most for δ =180
  - Worsening of precision is at most twice as bad: The measurement of δ at ESSνSB is quite robust against NSIs

Results



Over-optimistic precision in δ due to "ignorance" about the existence of NSIs

Results



Limits on NSI parameters from ESSνSB

Results

Parameter	Realistic limits	Optimistic limits	Existing limits
$\varepsilon^{s}_{\mu e}$	0.025	0.014	0.026
$\varepsilon^{s}_{\mu\mu}$	0.27	0.27	0.078
$\varepsilon^{s}_{\mu\tau}$	0.040	0.040	0.013
ε^{d}_{ee}	0.15	0.15	0.041
$\varepsilon^{d}_{e\mu}$	0.087	0.082	0.026
$\varepsilon^{d}_{\mu e}$	0.025	0.014	0.025
$\varepsilon^{d}_{\mu\mu}$	0.28	0.27	0.078
$\varepsilon^{d}_{\tau e}$	0.11	0.12	0.041
$\varepsilon^{d}_{\tau\mu}$	0.040	0.033	0.013

Conclusions & comments

- Non-standard effects arise from various possible BSM scenarios, and can affect neutrino oscillations.
- Current bounds on NSI parameters are at the 10^{-2} level. Future experiments like PINGU and HK will impose more stringent bounds. The neutrino factory can push them even further.
- We need more studies on source/detector NSIs.
- We need studies in the full parameter space, unless it is constrained by physical reasons. Yes, that includes the phases!
- The measurement of δ at ESSνSB is robust to the presence of NSIs
- ESSνSB can impose strong bounds on $\varepsilon^{s}_{\mu e}$ and $\varepsilon^{d}_{\mu e}$, which are more restrictive than the current bounds


THANK YOU

Analytical formula

$$
\begin{aligned}
P^{\rm vac}_{\nu_\mu^s\to\nu_e^d} &= 4s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&+ \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right)^2 c_{23}^2 s_{2\times12}^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right)^2 \\
&+ \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{13} s_{2\times12} s_{2\times23} \cos\delta_{\rm CP} \frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{2E} \\
&- 2\frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{13} s_{2\times12} s_{2\times23} \sin\delta_{\rm CP} \frac{\Delta m_{31}^2 L}{4E} \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&- 4|\epsilon_{\mu e}^s| s_{13} s_{23} \cos(\phi_{\mu e}^s + \delta_{\rm CP}) \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&- 2|\epsilon_{\mu e}^s| s_{13} s_{23} \sin(\phi_{\mu e}^s + \delta_{\rm CP}) \sin\frac{\Delta m_{31}^2 L}{2E} \\
&- 4|\epsilon_{\mu e}^d| s_{13} c_{2\times23} s_{23} \cos(\phi_{\mu e}^d + \delta_{\rm CP}) \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&- 2|\epsilon_{\mu e}^d| s_{13} s_{23} \sin(\phi_{\mu e}^d + \delta_{\rm CP}) \sin\frac{\Delta m_{31}^2 L}{2E} \\
&+ 4|\epsilon_{\tau e}^d| s_{13} s_{2\times23} s_{23} \cos(\phi_{\tau e}^d + \delta_{\rm CP}) \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&- |\epsilon_{\mu e}^s| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times12} c_{23} \sin\phi_{\mu e}^s \frac{\Delta m_{31}^2 L}{2E} \\
&+ 2|\epsilon_{\mu e}^d| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times12} s_{23}^2 c_{23} \cos\phi_{\mu e}^d \frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{2E} \\
&- |\epsilon_{\mu e}^d| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times12} c_{23} \sin\phi_{\mu e}^d \frac{\Delta m_{31}^2 L}{2E} \cdot \left[1 - 2s_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{2E}\right] \\
&+ 2|\epsilon_{\tau e}^d| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times12} s_{23} c_{23}^2 \cos\phi_{\mu e}^d \frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{2E} \\
&+ 2|\epsilon_{\tau e}^d| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{2\times12} s_{23} c_{23}^2 \sin\phi_{\mu e}^d \frac{\Delta m_{31}^2 L}{2E} \sin^2\frac{\Delta m_{31}^2 L}{4E} \\
&+ \mathcal{O}\left(\left[\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right]^3\right) + \mathcal{O}\left(\left[\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right]^2 s_{13}\right) + \mathcal{O}\left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2} s_{13}^2\right)
\end{aligned}
$$

0708.0152: Kopp, Lindner, Ota, Sato

Current status

$$|\varepsilon^{s}_{\mu e}| < 0.026 \quad , \quad |\varepsilon^{s}_{\mu\mu}| < 0.078 \quad , \quad |\varepsilon^{s}_{\mu\tau}| < 0.013$$

$$|\varepsilon^{d}_{ee}| < 0.041 \quad , \quad |\varepsilon^{d}_{\mu e}| < 0.025 \quad , \quad |\varepsilon^{d}_{\tau e}| < 0.041$$

$$|\varepsilon^{d}_{e\mu}| < 0.026 \quad , \quad |\varepsilon^{d}_{\mu\mu}| < 0.078 \quad , \quad |\varepsilon^{d}_{\tau\mu}| < 0.013$$

0907.0097: Biggio, Blennow, Fernandez-Martinez